

TRIPLE-PULSE INTEGRATED PATH DIFFERENTIAL ABSORPTION LIDAR FOR CARBON DIOXIDE MEASUREMENT—NOVEL LIDAR TECHNOLOGIES AND TECHNIQUES WITH PATH TO SPACE

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Abstract— The societal benefits of understanding climate change through identification of global carbon dioxide sources and sinks led to the desired NASA’s active sensing of carbon dioxide emissions over nights, days, and seasons (ASCENDS) space-based missions of global carbon dioxide measurements. For more than 15 years, NASA Langley Research Center (LaRC) have developed several carbon dioxide active remote sensors using the differential absorption lidar (DIAL) technique operating at the two-micron wavelength. Currently, an airborne two-micron triple-pulse integrated path differential absorption (IPDA) lidar is under development. This IPDA lidar measures carbon dioxide as well as water vapor, the dominant interfering molecule on carbon dioxide remote sensing. Advancement of this triple-pulse IPDA lidar development is presented.

Keywords—carbon dioxide; water vapor; triple-pulse laser; lidar; DIAL; IPDA

I. INTRODUCTION

The lack of spatially extensive, high-accuracy atmospheric CO₂ data limits the ability to construct accurate inverse estimates of the sources and sinks of the gas. ASCENDS study advocate an active CO₂ remote sensing mission to provide critical global CO₂ measurements [1]. Airborne full range-resolved DIAL measurements of CO₂ is beyond near-term technological capability. In absence of such capability airborne column dry-air volume mixing ratio of CO₂ (XCO₂) measurements weighted toward the boundary layer (BL) are ideal for studying CO₂ sources and sinks [1][2][3]. This is achieved using the IPDA lidar technique, which relies on much stronger hard target return signals rather than weak atmospheric scattering [4]. In addition, an airborne instrument provides an excellent complement to the temporally-rich but spatially sparse *in-situ* measurement network. The BL weighted XCO₂ data can be used to evaluate the ability of GOSAT and OCO-2 to detect spatial variability in lower tropospheric CO₂. Simultaneous airborne measurement of column dry-air volume mixing ratio of H₂O (XH₂O) enables the study of coupled carbon and water cycles [4][5][6].

For more than 20 years, researchers at LaRC have developed several high-energy and high repetition rate 2-μm pulsed lasers and other critical components for CO₂ DIAL instruments [7]. The 2-μm wavelength was targeted due to the existence of distinct absorption features for CO₂ at this wavelength region [4]. Currently, LaRC team is engaged in designing, developing and demonstrating a triple-pulsed 2-μm direct detection IPDA lidar to measure XCO₂ and XH₂O from an airborne platform [4][8][9]. The unique wavelength control

for each pulse allows measurement of the two most dominant greenhouse gases, simultaneously and independently, using a single instrument [10]. This work is an update for the 2-μm double-pulse airborne IPDA lidar for CO₂ measurement [11][12]. This paper provides background, status and details of the triple-pulse IPDA development, which enables several technologies for future space-based system for global CO₂ measurement [8].

II. TRIPLE-PULSE IPDA LIDAR TECHNIQUE

Based on the successful demonstration of the double-pulse IPDA lidar, the triple-pulse IPDA lidar transmitter generates three successive laser pulses for every pump pulse [4][11][12]. The pump repetition rate is set to 50 Hz. The three pulses are 150 to 200 μsec apart and set to three different wavelengths, as shown schematically in Fig.1. Using an enhanced wavelength control scheme the wavelength of each of these pulses can be tuned and locked at different wavelength, as marked in Fig.2. One scenario of wavelength selection is demonstrated in the same figure. The CO₂ on and off-line wavelengths are selected around the R30 line, so that both would have similar H₂O absorption to minimize water vapor interference on CO₂ measurements. Similarly, H₂O on- and off-line are selected around the nearest H₂O absorption peak such that carbon dioxide interference is minimized in the H₂O measurement. However, both CO₂ on-line and H₂O off-line measurements share the same wavelength, which enables simultaneous measurement of both molecules with three pulses rather than four pulses almost independently while avoiding interference from each other [4]. Other different measurement scenarios could be achieved with the same IPDA instrument just by tuning and locking the operating wavelengths of the three pulses to different positions.

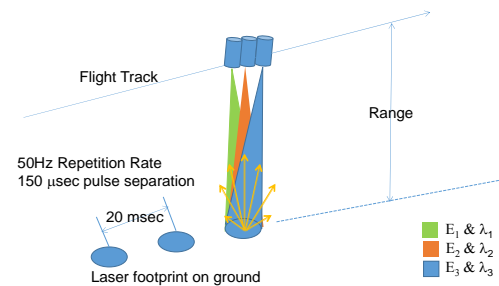


Figure 1. Airborne nadir 2-μm triple-pulse IPDA lidar concept. Each pulse is generated with different wavelength and energy. The three pulses are transmitted every 20 ms, equivalent to 50 Hz repetition rate. Pulse separation of 150-200 ms results in higher than 95% laser footprint overlap above 4 km altitude.

For example, wavelength tuning allows measuring CO₂ with two different weighting functions simultaneously as shown in Fig.3. Fig.3 indicates that the selected CO₂ on-line wavelength is optimized for near-surface measurements. Shifting this wavelength by 67 or 75 pm would tune the weighting function to optimize measurements in the BL or lower troposphere. This tuning feature results in a unique adaptive targeting capability. For an airborne IPDA lidar, adaptive targeting would tune and lock the instrument sensing wavelength to meet certain measurement objective depending on the target or Earth's surface condition and environment. Table 1 lists the double-pulse and triple-pulse 2- μ m IPDA lidar transmitter parameters as compared to transmitter requirements for CO₂ space-based active remote sensing. These space-based requirements were set by the European Space Agency (ESA) for a future CO₂ active remote sensing mission at the 2- μ m wavelength [3][4][12].

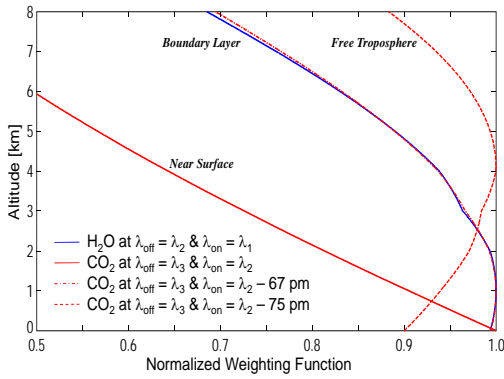


Figure 3. H₂O and CO₂ pressure-based normalized weighting functions versus altitude at selected spectral positions for an airborne nadir pointing IPDA measurement. H₂O and CO₂ measurements are weighted to the boundary layer and near the surface, respectively, for operating wavelength shown in Fig.2. Tuning CO₂ on-line wavelength 67 and 75 pm away from the selected location optimize the IPDA measurement to within the boundary layer or lower troposphere. [4]

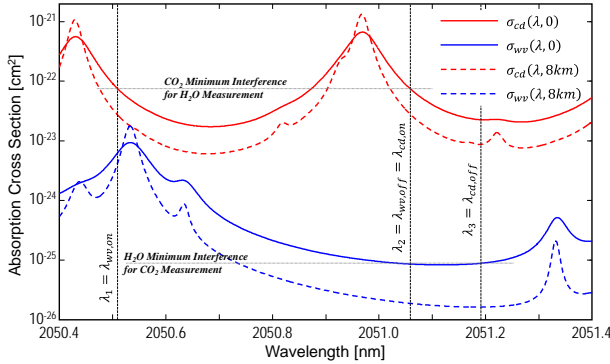


Figure 2. Comparison of the H₂O and CO₂ absorption cross-section spectra, σ_{wv} and σ_{cd} , respectively, at ground (0 km) and mid-altitude aircraft (8 km). Temperature and pressure profiles used in the calculation were obtained from the US Standard atmospheric model. Vertical lines mark the instrument operating wavelengths for CO₂ and H₂O independent measurements. Note that λ_1 is the H₂O on-line, λ_2 serves as the H₂O off-line, and the CO₂ on-line and λ_3 is the CO₂ off-line. The horizontal lines point to minimization of molecular interference errors [4].

III. TRIPLE-PULSE IPDA LIDAR TECHNOLOGY

The 2- μ m triple-pulse IPDA lidar consists of a laser transmitter, receiver and data acquisition system. The triple-pulse IPDA laser transmitters is based on the Ho:Tm:YLF high-energy 2- μ m pulsed laser technology [7]. The generated 2- μ m laser beam is transmitted coaxially with the receiver telescope after beam expansion. Energy monitors, installed inside the laser enclosure, detect and measure the energy of each of the transmitted pulses [11]. The exact wavelengths of the three pulses are controlled by a wavelength control unit.

Table 1. Comparison of CO₂ active remote sensing state-of-the-art 2- μ m double-pulse and triple-pulse IPDA laser transmitters, developed at NASA LaRC, with ESA space requirements [4][7].

	Current Technology	Projected Technology	Space Requirement
Transmitter	Single-Laser	Single-Laser	Two Lasers
Technique	Double-Pulse	Triple-Pulse	Single-Pulse
Cooling	Liquid	Conductive	---
Wavelength (μ m)	2.051	2.051	2.051
Pulse Energy (mJ)	100 / 50	50 / 15 / 5	40 & 5
Repetition Rate	10 Hz	50 Hz	50 Hz
Power	1.3 W	3.5 W	2.25 W
Pulse Width (ns)	200/350	30/100/150	50
Optical Efficiency	4.0%	5.0%	5.0%
Wall-Plug Efficiency	1.4%	2.1%	>2.0%
Multi-Pulse Delay	200 μ s	200 μ s	250 \pm 25 μ s
Transverse Mode	TEM ₀₀	TEM ₀₀	TEM ₀₀
Longitudinal Modes	Single Mode	Single Mode	Single Mode
Pulse Spectral Width	2.2MHz	4-14MHz	> 60MHz
Beam Quality (M ²)	2	2	< 2
Freq. Control Accuracy	0.3 MHz	0.3 MHz	0.2 MHz
Seeding Success Rate	99	99	99
Spectral Purity	99.9%	99.9%	99.9%

A. Triple-Pulse Laser Transmitter

The Ho:Tm:YLF triple-pulse laser is end pumped using 792 nm AlGaAs laser diode arrays. This external pumping targets the Tm, which transfer the stored energy to the Ho relying on the different excitation lifetime. Relative to the pump pulse, Q-switch triggers produces up to three successive laser pulses with relatively controlled energies and pulse-widths. Fig. 4 compares the generated output laser energies for single, double and triple-pulse operation versus the pump laser energy. For three pulse arrangement time separation is approximately 150-200 μ s. Thermal analysis was conducted to design proper heat dissipation out of the laser crystal to avoid permanent damage. A prototype oscillator with triple pulsing capability has already been demonstrated. Fig.5 shows a single-shot pulse record generated from the oscillator. Final laser configuration including thermal analysis and alignment optimization is currently on going to achieve higher energies.

B. Wavelength Control

The objective of the wavelength control unit is to provide the required seeding for each of generated pulses. A study indicated that ± 1 MHz on-line wavelength jitter is the dominant transmitter systematic error source using this triple-pulse IPDA lidar for CO₂ measurements [4]. This drives the need for a precise wavelength locking mechanism to reduce such error. The exact wavelengths of the pulsed laser transmitter are controlled by the wavelength control unit. The unique wavelength control of the triple pulses uses a single semiconductor laser diode, obtained from NASA Jet Propulsion Laboratory [13] and provides three different seeds of any frequency setting within 35 GHz offset from the locked CO₂ R30 line center reference [10]. This unit includes several electronic, optical and electro-optic components which were acquired and characterized at NASA LaRC. Laser diode driver electronics results in a wavelength jitter of ± 6.1 MHz. This jitter is significantly reduced to ± 650.1 kHz using center line locking electronics, which meets the jitter limit objective [4]. Fig. 6 shows an optical spectrum analyzer scans for the seeding wavelengths at 6, 16 and 32 GHz offset from the center line locking. Proper filters are included to eliminate harmonics from the generated wavelengths to maintain spectral purity.

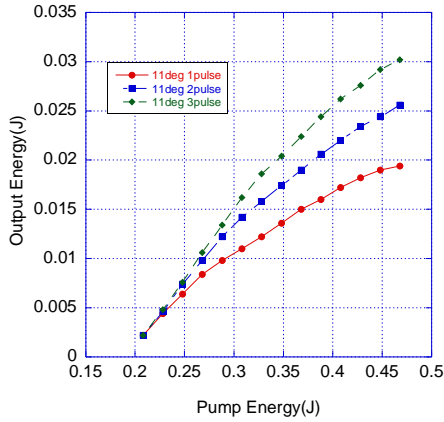


Figure 4. Total output pulse energy versus pump laser energy for the 2- μ m IPDA transmitter for single-, double- and triple-pulse operation. Data presented for 50Hz repetition rate and 2.5 ms long pump pulse.

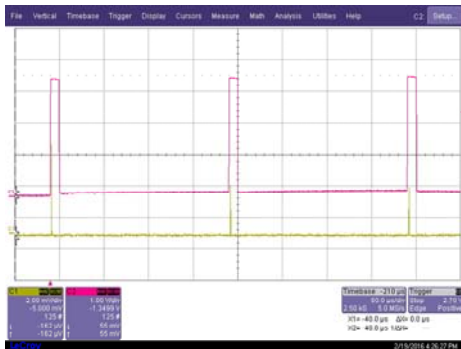


Figure 5. Oscilloscope record for a successful triple-pulse operation of the 2- μ m IPDA transmitter. The record shows the profiles of the three pulse (yellow) relative to the Q-switch triggers (red).

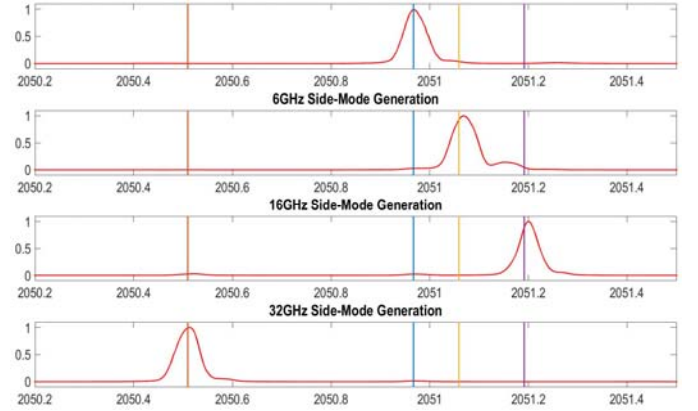


Figure 6. Optical spectrum analyzer scans for the reference wavelength locking to the CO₂ R30 line (top) and the different generated seeding wavelengths for the triple-pulse IPDA transmitter. Vertical lines mark the center line reference (blue), 6 GHz (yellow), 16 GHz (purple) and 32 GHz (orange) spectral positions. Lines are broadened due to the analyzer resolution.

C. IPDA Receiver and Detection Systems

Similar to the double-pulse IPDA, the 2- μ m triple-pulse IPDA lidar receiver, shown schematically in Fig. 7, consists of a 0.4 m Newtonian telescope that focuses the radiation onto 300 μ m diameter spot. The telescope secondary mirror is a two surface dichroic flat. One surface turns the return radiation 90° to the side integrated aft-optics. The opposite surface is used to transmit the expanded laser beam coaxially with the telescope. A single automated mount is used for bore-sight alignment. The radiation collected by the telescope is focused, collimated, filtered then applied to a 90/10 beam splitter. The 90% signal channel is an exact replica of the double-pulsed lidar using an InGaAs pin photodiode detection system. The 10% channel is planned to be used with an advanced HgCdTe (MCT) electron-initiated avalanche photodiode (e-APD) detection channel. These MCT e-APD devices are space-qualifiable and were validated for airborne lidar operation at 1.6- μ m at NASA Goddard Space Flight Center (GSFC) [14]. In co-ordination with NASA Earth Science Technology Office (ESTO), LaRC is collaborating with GSFC to integrate this detector into the 2- μ m IPDA. This e-APD exhibit less than 0.5 fW/Hz^{1/2} noise-equivalent-power (NEP) and is expected to enhance the 2- μ m IPDA detection performance by expanding the dynamic range and reducing random errors.

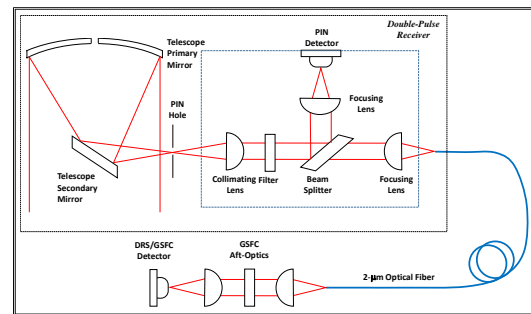


Figure 7. 2- μ m triple-pulse IPDA receiver system, integrated based on the previous double-pulse system. The receiver consists of a telescope, aft optics with high-signal InGaAs channel and low-signal e-APD channel. The e-APD channel is coupled through an optical fiber through additional aft-optics.

MCT e-APD are sensitive to IR radiation up to 4- μ m. Therefore, a cold narrow band-pass filter is desired to limit the device background. In co-ordination with ESTO, LaRC collaborated with GSFC to integrate the detector into the triple-pulse 2- μ m IPDA lidar. This e-APD comes with 4 by 4 pixel format (80 \times 80 μ m² pixel area) with read-out electronics that enable access to each pixel through individual TIA. An output summing amplifier would produce the sum of specific number of pixels as selected by the operator. The detector is integrated inside a vacuum chamber, which allows cooling the device with cryo-cooler down to 70 K to reduce dark current and noise. The e-APD and readout electronics are integrated inside a rack mountable chassis, shown in the same figure, which includes vacuum circuit for thermal isolation. Additional custom designed aft-optics allows focusing the radiation onto selected number of pixels. The e-APD custom aft-optics is coupled to the IPDA aft-optics through a 2- μ m optical fiber, as shown in Fig. 7. Work efforts at GSFC included 2- μ m cold filter integration to the detector chamber, detector assembly testing, additional aft-optics design with optical fiber coupling [14][15].

IV. CONCLUSIONS

A 2- μ m double-pulse IPDA lidar instrument have been developed at NASA LaRC. This instrument was validated for active remote sensing of carbon dioxide in the atmosphere. As an upgrade, a 2- μ m triple-pulse IPDA lidar instrument is being developed at NASA LaRC. This novel active remote sensing IPDA instrument targets and measures both atmospheric carbon dioxide and water vapor. Wavelength selection and laser transmitter operation allows measuring both species independently and simultaneously. This would be the first demonstration of measuring two different atmospheric molecules with a single instrument. The instrument design is based on knowledge gathered through the previously successful 2- μ m double-pulse IPDA. Critical enhancements were implemented in the new triple-pulse design that advances the technology. These enhancements includes both the transmitter and receiver. For the transmitter, modifications include triple-pulse operation of the laser, laser timing control updates and wavelength control design. In the receiver, updates includes telescope integration, data acquisition system and additional high performance e-APD detector. The e-APD detector supplied by NASA GSFC, is a state-of-art, space qualifiable device that was validated for lidar applications. Combining both the 2- μ m triple-pulse transmitter with this new detector in a single instrument will result in a CO₂ IPDA lidar with enabling technology, which meets or exceeds space requirements. Work progress of the 2- μ m triple-pulse IPDA program is on schedule. Instrument validation plans are under discussions to collaborate with different institutes with similar interests.

ACKNOWLEDGMENT

This work was funded and supported by NASA Earth Science Technology Office. The authors acknowledge the

support of NASA Jet Propulsion Laboratory and NASA Goddard Space Flight Center.

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